Trilateral Impact Assessment Framework for Automation in Road Transportation

Trilateral Impact Assessment Sub-Group for ART

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1 Introduction

Automated vehicles (AVs) have the potential to transform the world's road transportation system. Benefits realized could include traffic safety (automobile crashes are a leading cause of accidental deaths), transport network efficiency (most cities experience significant traffic congestion), energy/emissions (oil consumption, air pollution and greenhouse gas emissions are of worldwide concern) and personal mobility (a substantial portion of the driving-age population does not drive). AVs are being introduced into a complex transportation system. Second order impacts, such as the possibility of increased travel leading to more congestion and emissions, are of significant concern. The purpose of this document is to provide a high-level framework for assessment of the impacts of road traffic automation.

Members of the Trilateral Working Group on Automation in Road Transportation (ART WG)[1] are working to address the complexity of AV impacts. European researchers are looking at the possibility of applying the Field Operational Test Support Action's framework (FESTA, FOT Net 2016) to automation and sketching the mechanisms through which automation potentially affects our lives. The United States Department of Transportation has sponsored development of a modelling framework that includes the areas of safety, vehicle operations, personal mobility, energy/emissions, network efficiency, travel behavior, public health, land use, and socio-economic impacts. Japan is developing models of CO_2 impacts and is planning to start large scale field operational tests in late 2017 under SIP-adus.

To coordinate the impact assessments performed in the field of automated driving, the ART-WG established an Impact Assessment sub-group in 2015. The motivation was the realization that, as field tests are expensive and mostly done on a small scale, international harmonization would be in everyone's interest. With a harmonized approach, tests and studies can be designed to maximize the insight obtained and to arrange complementary evaluation across the world. Harmonization would also facilitate meta-analysis.

The framework presented in this document includes some new material but is partly based on both the US DOT and FESTA frameworks. It also draws from insights obtained at the following workshops:

- FOT-Net Data workshop 'A common methodology for automation FOTs and pilots', Leeds, UK, February 2016
- ITS European Congress, SW3 'Towards a methodology for Field Operational Tests (FOTs) for automated vehicles', Glasgow, UK, June 2016
- AVS2016 Impact Assessment Break-out session, San Francisco, US, July 2016
- ITS World Congress, Melbourne, Australia, October 2016
- SIP-adus, Tokyo, Japan, November 2016

Governments may use this framework to support policy analysis and long-range scenario-based planning, where various automation futures are envisioned. Automakers and after-market equipment manufacturers may use it to better understand the potential benefits of their offerings. Designers of field tests (FOTs and

[1] The European Commission (EC), the United States Department of Transportation (USDOT) and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan have a long history of cooperation on Cooperative Intelligent Transportation Systems (C-ITS) activities. The Trilateral Automation in Road Transportation Working Group (ART WG) was established by approval of the Steering Group in October 2012.

pilots) may use it to ensure that the information gathered maximizes the value of the test, and those making the impact assessment for the automation of road transportation can use it as a starting point in design of their evaluation work.

This impact assessment framework gives recommendations in Chapter 2 for classifying automation implementations and determining impact areas to be assessed. Chapter 3 presents the impact mechanisms through which automated driving is expected to impact our life, covering both direct and indirect impacts. Chapter 4 provides recommendations for experimental procedure and Chapter 5 for data sharing. Conclusions are made in Chapter 6.

2 System and Impact Classification

This section describes a framework for assessing the impacts of AV applications. It explains direct and indirect impacts, and the importance of classifying the system before launching into detailed analysis. It then explains each type of impact area in further detail, including providing a list of proposed key performance indicators (KPIs).

AV impacts may be divided into two large groups: direct and indirect. Figure 1 depicts the impact areas. Direct impacts are those which have a relatively clear cause-effect relationship with the primary activity or action. They are generally easier to capture, measure and assess, and are often (though not always) immediate to short-term in nature. In Figure 1, they are in the upper left, and include safety, vehicle operations, energy/emissions and personal mobility. The others are indirect impacts. Indirect impacts can be characterized as secondary, tertiary, or still further removed from the original direct impact. Indirect impacts summarize the broader effects of the individual direct impacts and are produced as the result of a path/chain of impacts, often with complex interactions and external factors. They are typically more difficult to measure and are longer than the time horizon of a field test.[2]

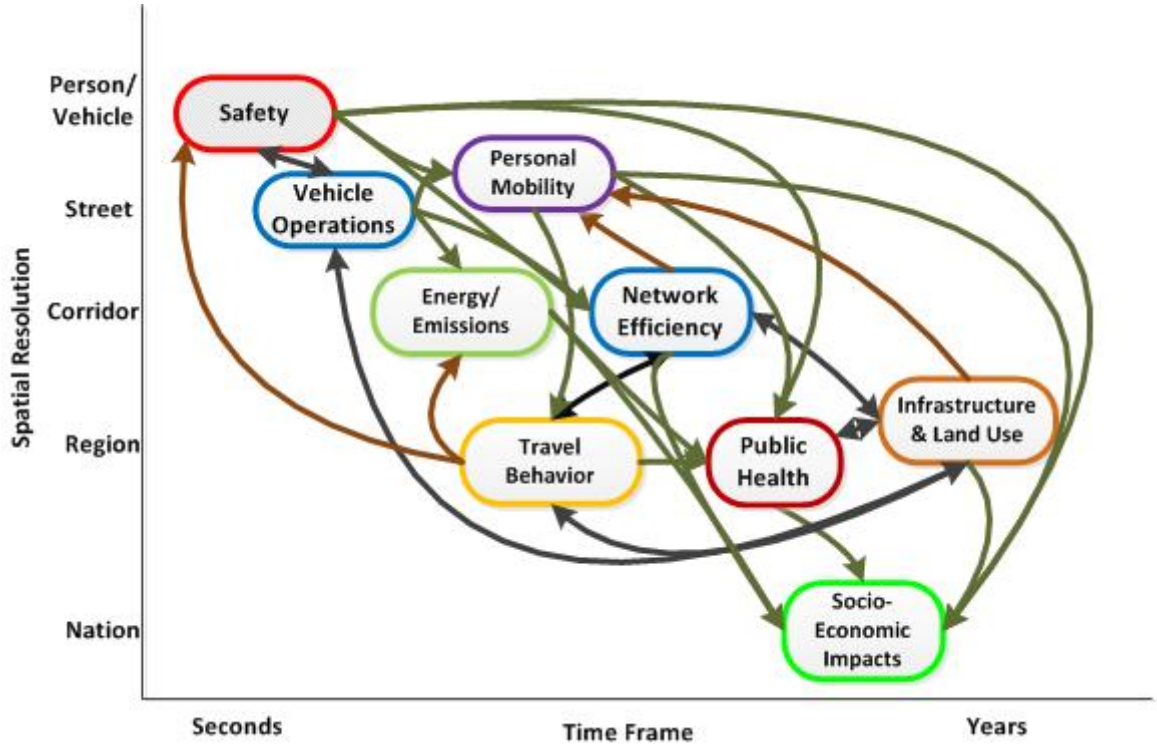

Figure 1. Impact Areas

Milakis et al. (2015) discuss first order (i.e. direct) and second and third order (indirect) impacts and liken them to the "ripple effect" used for 'sequentially spreading' events in economics and other social science fields. They note, however, that the parallel is not exact: as shown in Figure 1, there can be feedback from

[2] This explanation is inspired by that of direct and indirect environmental impacts of road development in Roads and the Environment - a Handbook (World Bank 1997)

higher-order to lower-order impacts, and as that implies, impact orders may not be in sequence chronologically.

2.1 Classification of the system and design domain

As a first step in setting up the analysis of a given implementation of vehicle automation, it is important to specify the description of the system and the service for which impact assessment is made. Otherwise, researchers risk comparing very different services even though they have a similar design domain. FESTA Handbook (FOT-Net 2014) addresses this classification through specifying use cases. Description of the ART system or service should include (at least):

- Function(s) within the transportation system (e.g., passenger, goods, mixed service, short v. long trips.)
- Vehicle type(s) (e.g., passenger vehicle, mini bus, large bus, truck, etc.)
- SAE level of automation and available automated driving functions
- Penetration rate of the technology (AVs only or mixed traffic)

An example of a classification process from the CityMobil2 project for automated transport systems is shown in Figure 2. A list of elements from this example, specific to public transport, follows. In planned FOTs, a similar classification exercise should be completed for other types of services to ensure impact assessment results are presented in the appropriate context for applying results, harmonization, and for future meta-studies.

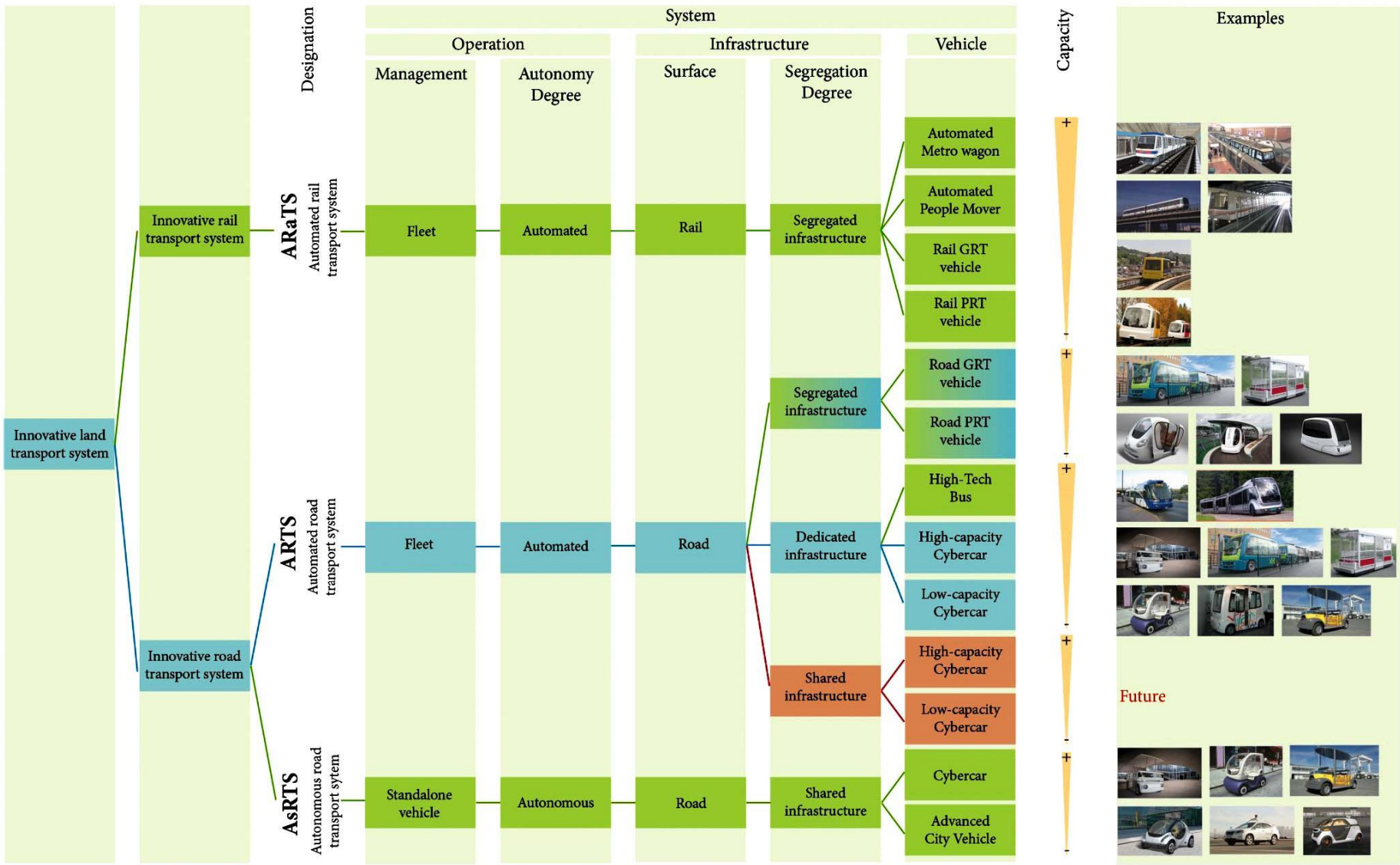

Figure 2. Automated transport systems classification according to CityMobil2 project (Kyomans et al. 2013).

Figure 2 classifies the transport systems by:

- Need for mechanical guidance: whether the system relies on guidance from the infrastructure, such as rails. Automation tends to blur the boundaries between road and rail making possible unprecedented synergies (e.g., small automated public transport vehicles could use the metro tunnels at night when it is no longer practical to keep the metro running).
- Level of operation: whether the vehicles are part of a fleet, and whether they need some degree of control from a control system. If the vehicles need external control they are automated but not autonomous; if they can take any decision without any form of communication or cooperation, they are autonomous.
- Degree of segregation of infrastructure: the infrastructure can be either fully segregated (accessible only to vehicles which are part of the system and protected against external intrusion); dedicated (certified to be accessible by the vehicles of the automated transport systems and also to some other users who will need to follow specific rules); or shared (any road infrastructure shared by any road user). Depending on this criterion several different transport systems become possible (e.g. the difference between personal rapid transport (PRT) and the Google autonomous car is mostly there and in fleet supervision). This criterion might even be applied only temporarily giving birth to other new forms of transport like a shared car featuring advanced driver assist systems when in use with a driver on shared infrastructure which could become completely automated for relocation purposes when driving itself on dedicated infrastructures such as bus lanes.
- Vehicle size: this might even be further varied by coupling more vehicles either without mechanical connection (platooning) or with such connection (convoying).

In addition to classifying the system, it is also essential to capture specific information on the operational design domain, including the infrastructure. Under FESTA, these elements are described as situational variables. These characteristics detail answers to questions such as: What is needed (road markings, signs, signals, mapping, V2X communications, winter maintenance) to support automated driving? More broadly, what is the operational design domain for the automation application? According to SAE J3016, the operational design domain may include geographic, roadway, environmental, traffic, speed, and/or temporal limitations. It may also include one or more driving modes. Examples of driving modes include expressway merging, high-speed cruising, and low-speed traffic jam.

Rather than using KPIs, infrastructure requirements can be characterized by a detailed description of the operational design domain, to indicate where the automation application is designed to function, and where it has been tested. Elements of the operational design domain include:

- Specific location where the automation system may operate
- Level of mapping needed where the automated system operates
- Type of road: number of lanes and carriageways, required markings, pavement type
- Types of intersections: merge, diverge, traffic signal, stop/yield sign
- Usage of road: exclusive to AVs, shared with other motor vehicles, shared with bicyclists and pedestrians
- Design speed
- Daytime / nighttime

- Types of road surface conditions: dry, wet, snowy, icy
- Visibility: clear, rain, snow, fog
- Temperature, atmospheric pressure

Classification and description of the system, infrastructure, and operational design domain enables more precise impact assessment and meta-analysis. Recommended direct and indirect impacts for investigation are listed below. In addition, while not impacts per se, other aspects of automation that should be assessed in a field test include the cost and the driver / other road user response to automation. These are also discussed in section 2.2.

2.2 Direct impacts

Direct Impacts are those that can be measured in an FOT. They then can be scaled up to a regional or national level, and can lead to indirect impacts. For example, an FOT can measure driving conflicts (Safety), driver/traveler behavior, car following and intersection performance (Vehicle Operations), energy consumption and tailpipe emissions (Energy / Emissions), and the comfort of the user or the user's ability to multi-task while in the vehicle (Personal Mobility). FOTs can also provide insights into the infrastructure requirements of an automation application.

The following impacts are examples of what should be considered in the design of an FOT. For example, specialized use cases such as truck platooning may require a unique set of KPIs not applicable to other FOTs (e.g., number of platoon formed or what share of the vehicle km/miles was driven as part of a platoon). As part of its work in 2017, the Impact Assessment Sub-Group will continue to identify and refine KPIs based on current and planned FOTs and studies and identify those which are the highest priority for international harmonization.

Response of drivers and other road users: How do the vehicle occupants or other road users respond to the automation application? For driver assistance systems, one question is whether the drivers use the system, on which kind of journeys or environments and in which kind of circumstances, and if relevant, what parameters they choose (for example, car following distance). The driver's degree of engagement with the driving task is also relevant (for example, is the driver treating a Level 2 system as though it is a Level 4 system?). For applications operating in mixed traffic environments, the behavior of other road users (drivers, pedestrians, bicyclists) is also relevant. KPIs will depend on the application being deployed, and may include:

- Driver / vehicle occupant characteristics (age, gender, license status)
- Whether the driver uses the automated driving (AD) system
- Degree of engagement with the driving task
- In-car activity (secondary tasks when driving, primary activities when not driving)
- Conflicts created by the driver
- Conflicts created by other road users (e.g., pedestrian stepping in front of an AV)

Vehicle Operations: Vehicle operations include acceleration, deceleration, lane keeping, car following, lane changing, gap acceptance: all affect road (network) capacity. Relevant automation applications include those which provide longitudinal and/or lateral control with respect to the road and other vehicles. KPIs include:

- Speed variation during constant speed travel (relevant to car-following)

- Lateral position variation (relevant to lane-keeping, and aerodynamics for platooning)
- Use of indicator signal
- Normal longitudinal acceleration and deceleration
- Lateral acceleration (around curves)
- Emergency deceleration
- Jerk (rate of change in acceleration; is relevant to passenger comfort)
- Car following performance (distance, time-headway, variation)
- Gap-acceptance at intersections or in lane changes
- Transfer of control between operator and vehicle (turning system on/off, manual overrule)

Safety: Ultimately, safety is measured as fatalities, injuries and property damage for vehicle occupants and other road users. Other road users may include pedestrians, bicyclists, slow-moving vehicles, construction workers and first responders. Nearly all AV applications, ranging from SAE Level 1 collision avoidance systems to SAE Level 5 self-driving vehicles, have potential safety impacts. A challenge with safety assessment is that actual crashes are rare events; therefore, proxy measures are often used. These measures may include selected traffic violations, instances where a human driver must take control of the vehicle, exposure to near-crash situations, and responses to near-crash situations. KPIs will be normalized to vehicle-km driven or vehicle-hours driven, and include:

- Number and severity of crashes by type (property damage, injury, and fatality), change in number of crashes (%)
- Number of conflicts encountered where time-to-collision (TTC) is less than a pre-determined threshold
- TTC at brake onset
- Minimum TTC (shortest TTC observed during a braking event)
- Instances with hard braking (high deceleration)
- Number of instances where the driver must take manual control
- False positives – instances where the vehicle takes unnecessary collision avoidance action
- Selected traffic violations[3]

Energy / Environment: The energy and emissions category includes both the energy consumption of the vehicle through a driving cycle, and tailpipe emissions of pollutants including greenhouse gases. The direct energy/emissions impacts come from the change in the driving cycle. Changes in vehicle propulsion (e.g., electric vehicles) may also have a significant effect on tailpipe emissions. KPIs include:

- Vehicle energy consumption (kWh, litres / 100 km or electric equivalent[4])
- Personal energy consumption (kWh / person-mile and kWh/ person)
- Total fossil (gasoline, diesel, CNG, LNG) energy consumption from highway transportation
- Noise levels along roads (in dB)

[3] Some violations may have little significance (e.g., traveling at 95 kph in a 90 kph zone), while others are of greater significance (e.g., passing through a red signal several seconds after it has turned red)
[4] 1 gallon (4.54609 litres) of gasoline = 33.7 kWh. See http://www.fueleconomy.gov

- Tailpipe[5] carbon dioxide (CO_2) emissions
    - Total
    - Per person
    - Per vehicle-mile
- Tailpipe criteria pollutant[6] emissions
    - Total
    - Per person
    - Per vehicle-mile

Personal Mobility: Mobility from a user's standpoint includes journey quality (comfort, use potential of in-vehicle time), travel time, cost; and whether the travel option is available to someone (e.g., a non-motorist). It also includes equity and accessibility considerations. The higher levels of automation will have the most significant impacts, by providing mobility for non-motorists and enabling multi-tasking. These include first mile / last mile services and accessibility applications. Challenges in measuring personal mobility impacts include the variety of sub-populations who may be affected in different ways, and the difficulty in assessing the actual value of automation to a person based on survey data. Travel time indicators are generally evaluated at the network level – rather than the individual level. Network efficiency is addressed in Section 2.3 below. KPIs for this area may also be measured as user friendliness and acceptance of systems.

KPIs include:

- Total time spent travelling (e.g. per day)
- % of time or population for which a travel option is available
- User perceptions of quality, reliability, and comfort expressed e.g. on Likert scale
- User perception of travel time changes
- Type and duration of activities when not operating the vehicle (high levels of automation)

Cost: Once an automation application has moved out of prototyping, and into production, what is a reasonable estimate of the capital and operating cost for the technology? This is important for assessing the future business case for deployment and ultimate usage. Key performance indicators (KPIs) include:

- Estimate of capital cost per vehicle for the deployed system
- Estimate of cost of purchased AV (market price)
- Estimate of operating cost for the deployed system (per vehicle-hour or per vehicle-km)

2.3 Indirect impacts

In assessing indirect impacts, note that service offerings and fleet composition might change. For example,

[5] In assessing automation benefits, it may be necessary to assume that types of fuel used by automated and non-automated vehicles are the same, at least in the near-term. It may be beyond the scope of an FOT to assess the CO_2 emissions from electricity generation.

[6] U.S. criteria pollutants include ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide and lead. See http://www.epa.gov/airquality/urbanair/

- With better crash avoidance, it may be possible to use lighter-weight vehicles (with impact e.g. on material and energy use or emissions) and avoid congestion (with impact on network efficiency)
- The advanced control systems used for automation may also contribute to electrification (with impact on energy use and emissions)
- If there is no human driver, the layout of the vehicle might change (with impact e.g. on energy use)
- Without the labor cost of a human driver, it may become economical to use smaller vehicles for both trucking and transit (with impact on energy use and network efficiency).

We are also concerned with how different groups of people might be affected: non-motorists, professional drivers, etc.

Network Efficiency: Network efficiency refers to lane, link and intersection capacity and throughput in a regional transport network. It also refers to travel time and travel time reliability. Improved safety may improve network efficiency via reduced incident delay. Also, changes in vehicle operations (e.g., car following) will affect network efficiency. In addition, changes in transport modes or mileage driven by AVs affect it, too. KPIs include the following, depending on the level of detail desired:

- At the road segment level:
  - Capacity at design speed
  - Maximum capacity
  - Free flow speed
  - Median speed
  - 5th percentile speed - addresses “worst case” reliability
- For an intersection approach
  - Vehicles per hour through a particular intersection approach (throughput), normalized to number of lanes and proportion of green time.
- For a corridor
  - Average travel time (minutes)
  - 95th percentile travel time (minutes). This measure addresses travel time reliability.
- For a region
  - Total number of trips (used for normalization)
  - Total travel distance (used for normalization)
  - Total travel time
  - Average trip duration
  - Average trip length
  - Average travel speed
  - Total travel delay

Travel Behavior: A traveler may respond to AV options, including new service offerings, by changing travel behavior. There may be more or fewer trips. Modes, routes and destinations may change. Higher level automation applications that have a significant effect on personal mobility or labor could have a significant effect on travel behavior. KPIs include:

- Number and type of trips
- Share of transport modes (modal split)
- Share of used road types

- Total mileage/kms travelled
- Network-level travel time savings

Asset Management: Automation may affect infrastructure assets required in several ways, though significant uncertainty still remains in this area. Because of this uncertainty, identifying specific indicators is difficult, but the examples listed suggest some areas in which infrastructure assets may be affected:

- Number of lanes and lane widths
- Use of hard shoulder (for hard-shoulder running or as emergency stop area for mal-functioning AVs)
- V2I infrastructure used by automation
- Size and weight implications of changed fleet composition
- Effect of travel behavior changes on trip making. If travelers respond to automation by making more trips, more road capacity may be needed. On the other hand, if automation leads to greater us of shared, rather than owned, vehicles, the infrastructure required for parking may be reduced. Changes in trip making may affect the assets required.

Public Health: Automation may impact the health (physical and mental) of individuals and entire communities, via safety, air pollution, amount of walking and bicycling, as well as access to medical care, food, employment, education and recreation. KPIs include:

- Concentrations of air pollutions listed in Energy/Emissions (under direct impacts)
- Daily-adjusted life years
- Modal share and total mileage travelled (kms) by active modes of transportation
- Perception of safety and comfort of vulnerable road users

Land Use: Automation may affect the use of land for transport functions (e.g., parking, road geometry). Longer term land use changes may include community planning i.e. location and density of housing, road network design, employment and recreation. The number of factors that contribute to long-term land use changes makes distinguishing those changes contributed by automation a particular challenge. Additional research in this area would be required to establish meaningful KPIs.

Socio-Economic Impacts: Improved safety, use of time, freight movement, travel options (for motorists and non-motorists), public health, land use and effects of changed emissions (including climate change) will have longer-term economic impacts. Automation may also have substantial impact on labor markets and industries. Assessment in this area continues to evolve. Some preliminary KPIs include the following:

- Gross Domestic Product: total, per capita, and per hour worked
- Total factor productivity / multifactor productivity estimates
- Work time lost from traffic crashes [hours per year, overall and per capita; monetary value]
- Work time lost from illnesses related to air pollution
- Work time gained due to ability to multitask while traveling
- Labor force participation rate – overall and for non-drivers.

3 Impact mechanisms

3.1 General impact mechanisms for assessment

Nine basic impact mechanisms were formulated for automation studies:

1. Direct modification of the driving task, drive behavior or travel experience
2. Direct influence by physical and/or digital infrastructure
3. Indirect modification of AV user behavior
4. Indirect modification of non-user behavior
5. Modification of interaction between AVs and other road-users
6. Modification of exposure / amount of travel
7. Modification of modal choice
8. Modification of route choice
9. Modification of consequences due to different vehicle design

The purpose of these mechanisms is that the assessment covers systematically the intended and unintended, direct and indirect, short-term and long-term impacts of both AV-users and non-users. It is recommended that these mechanisms be used for all impact areas of AD studies.

The basis for the mechanisms was the nine safety impact mechanisms of intelligent transport systems of Kulmala (2010) which were adapted from the mechanisms formulated by Draskóczy et al. (1998). Kulmala (2010) aimed with his safety assessment framework to eliminate overlaps and thereby the risk of "double counting", to test the validity of any single mechanism, and to operationalize the mechanisms for assessment purposes. The same principles are also valid for automation studies. The aim is to make the mechanisms non-overlapping and all-inclusive, i.e., that all impacts would fall under some and (preferably) only one mechanism. In cases in which an impact falls under two (or more) mechanisms, it is preferable to select the most suitable one.

Supporting questions that help to understand what is meant by each mechanism are listed below. Note that all questions might not be relevant for all concepts of AD.

1. <u>Direct</u> modification of the driving task, drive behavior or travel experience
    - § What are the direct impacts due to the vehicle driving by itself (driving task, in-car or remote)?
    - § What are the direct impacts of differences in drive behavior of AV and human driver (in-car or remote) for e.g. car-following, target speed, used speed or situation awareness?
    - § What are the direct impacts of handover from AV to driver in non-full automation?
    - § What are the direct impacts of AV including potentially more active safety systems than the baseline?
    - § What are the direct impacts of information and warnings provided by the vehicle sensors to the human driver (SAE 1-2)?
    - § What are the direct impacts of the non-driving related in-car activities?
    - § What are the direct impacts on travel experience (e.g. comfort, nausea)?

2. <u>Direct</u> influence by physical and/or digital infrastructure
    - § What are the direct impacts due to connectivity (information, warnings, platooning, entertainment, including failures in these: bugs, blind spots, service breaks and hacking)?

- What are the direct impacts due to the having digital maps in use and to the map quality?
- What are the direct impacts due to physical infrastructure in case it is different for AVs (e.g. special lanes)?

3. Indirect modification of AV user behavior
   - What are the (long-term) impacts of change in driving skills (in-car or remote)?
   - What are the (long-term) impacts of behavioral adaptation in drive behavior of the users of AV (when driving in non-AD mode)?
   - What are the impacts of behavioral adaptation when driving in AD mode (long-term impacts on allocation of attention and in-car activities)?
   - What are the impacts of unintended use of AV (e.g. use of AV when not fit to drive; use of low-level AV as high-level)?
   - What are the impacts of failures in connectivity or other features of AV?

4. Indirect modification of non-user behavior
   - What are the impacts of the behavioral adaptation of the other road users (i.e. imitation of AV drive behavior)?

5. Modification of interaction between AVs and other road-users
   - What are the impacts on interaction (communication, resolution of encounters) between the AV and other road users (on links and in intersections)? E.g.,
     - Between connected AVs
     - Between connected AV and connected non-AV
     - Between AV and non-connected vehicles
     - Between AV and other road users
   - What are the impacts of the new forms of interaction (including teasing of AV[7]) between the AVs and other road users?

6. Modification of travel behavior (exposure / amount of travel)
   - What are the impacts (via change in vehicle miles/kilometers travelled or hours travelled) on the number of journeys, e.g., due to impact on comfort and ability to travel?
   - What are the impacts on the length of journeys?

7. Modification of travel behavior (mode choice)
   - What are the impacts on use of different transport modes / transport mode share (e.g., due to impact on costs, availability, attractiveness, ease-of-use or security of different modes)?

8. Modification of travel behavior (route choice)
   - What are the impacts of AVs' routes (road type, level of congestion) being different from those of the baseline?

9. Modification of consequences due to different vehicle design
   - What are the impacts of the AV design being different from the baseline (outside design, inside design, engine)?
   - What are the impacts of AV including more passive safety systems than baseline?

[7] e.g. by jumping to the front of the AV (just for 'fun') to make it stop

Interactions (Mechanism 5) with other road users are an essential component of driving activity. In many cases, for example before a lane change or before a left turn with oncoming traffic, drivers often interact with other traffic participants in order to purposefully agree on a future motion plan. Currently, human drivers communicate their intent and anticipate others' intent based on explicit communication means, for example flash of headlights, direction lights, horn, and on implicit cues, for example speed variation, lateral position variation. Similar means are used by pedestrians and other traffic participants to anticipate drivers' intent. Such interactions are expected to gradually change, when the interacting agent is an automated vehicle and not a human driver, following the functionalities and capabilities of automated vehicles.

Table 1 provides some examples of what each mechanism could mean in different areas of ART impact assessment studies.

Table 1. Examples of different mechanisms per impact area

Mechanism	Safety	Personal mobility	Environment	Efficiency
1. Direct modification of the driving task, drive behavior or travel experience	Impact on crashes via changes in · situational awareness · perception · speed · car-following behavior · reaction times due to direct changes in drive behavior (AV, human driver and in handover) or active safety systems or vehicle sensor based information systems (in non-AD mode)	Impact on travel quality via changes in travel experience, i.e. · comfort · stress · nausea · possibility for non-driving related in-vehicle activities due to direct changes in drive behavior	Impact on emissions via changes in · speed patterns · acceleration / deceleration · car-following behavior (especially platooning) due to direct changes in drive behavior	Impact on throughput due to direct changes in · speed patterns · car-following behavior · gap acceptance
2. Direct influence by physical and/or digital infrastructure	Impact on crashes via same changes as above due to connectivity and infrastructure quality	Impact on quality of travel due to · connectivity (direct impact e.g. on uncertainty and infotainment) · direct changes (e.g. nausea) due to changes in the smoothness of travel due to differences in quality of physical infrastructure	Impact on emissions via same changes as above due to connectivity and differences in infrastructure quality	Impact on throughput due to connectivity, infrastructure quality and change in the use of carriageway width
3. Indirect modification of AV user behavior	Impact on crashes due to long-term behavioral adaptation of AV user (e.g. reallocation of attention resources, ability to drive / take over driving task)	Long-term impact on amount of travel (number and length of journeys) and used modes of transport via quality of travel	Impact via long-term behavioral adaptation of AV user, changes listed above in manual mode	Impact via long-term behavioral adaptation of AV user, changes listed above in manual mode
4. Indirect modification of non-user behavior	Impact on crashes due to imitation of AV drive behavior by non-AV users	Long-term impact on used modes due to change in feeling of safety of the non-AV users and due to change in social norms (if everyone else uses, so must I)	Impact on emissions due to imitation of AV drive behavior by non-AV users	Impact on throughput due to imitation of AV drive behavior by non-AV users

Mechanism	Safety	Personal mobility	Environment	Efficiency
5. Modification of interaction between AVs and other road-users	Impact on crashes due to change in detection and situation interpretation of other road-users	Impact on quality of travel due to smoothness of interaction with other road users (e.g., does the interaction create frustration by failing to meet expectations?); Impact on amount of travel (travel time) due to changes in the interaction.	Impact on emissions due to change in the smoothness of traffic flows caused by the difference in the interaction with other road-users	Impact on throughput (especially in intersections and on ramps) due to the difference in the interaction with other road-users
6. Modification of exposure / amount of travel	Impact on crashes due to change in total kms/miles travelled caused by change in destinations or number of trips due to e.g. perceived change in travel comfort and ease	Impact on amount of travel due to change in total time spent travelling due to perceived change in travel comfort and ease	Impact on emissions due to change in total kms/miles travelled caused by the change in destinations or number of trips due to e.g. perceived change in travel comfort and ease	Impact on throughput due to change in total kms/miles travelled caused by the change in destinations or number of trips due to e.g. perceived change in travel comfort and ease
7. Modification of mode choice	Impact on crashes due to change in mode selection (risk levels of different transport modes) caused by changes in relative attractiveness and costs of different modes	Impact on used modes due to change in relative satisfaction or attractiveness and costs of different modes	Impact on emissions due to change in mode selection (emission levels of different transport modes) caused by changes in relative attractiveness and costs of different modes	Impact on throughput due to change in modal share on traffic flow (different vehicle types' use of capacity e.g. as passenger car units)
8. Modification of route choice	Impact on crashes via changes in the used road types (their relative risk levels)	Impact on travel quality due to satisfaction on used routes	Impact on emissions due to different speed patterns on different routes (road types)	Impact on throughput via distribution of demand on road network (capacity utilization rate on different roads)
9. Modification of consequences due to different vehicle design	Impact on crashes via differences in passive safety systems of vehicles eliminating and mitigating crash consequences	Impact on travel quality via differences in vehicle design (e.g. seating, noise)	Impact on emissions due to differences in aerodynamics and engine design	Impact on throughput due to changes in sizes (length) of vehicles

3.2 Impact paths for ART

As there are different levels of automation and different concepts of automation, no single approach can be recommended for all impact assessments. However, the charts below indicate potential impact paths starting from direct impacts on vehicle operations, driver or traveler, quality of travel and transport system. The paths are presented per impact areas for some of them: safety, network efficiency, environment and quality of life / equity / health. These graphs are not inclusive but they can be used as a starting point for systematically determining the impact paths for systems and impact areas which are under investigation. Naturally, there are strong links between impact areas, e.g., safety impacts affecting efficiency and environment. Thus, assessment of indirect impacts is also recommended.

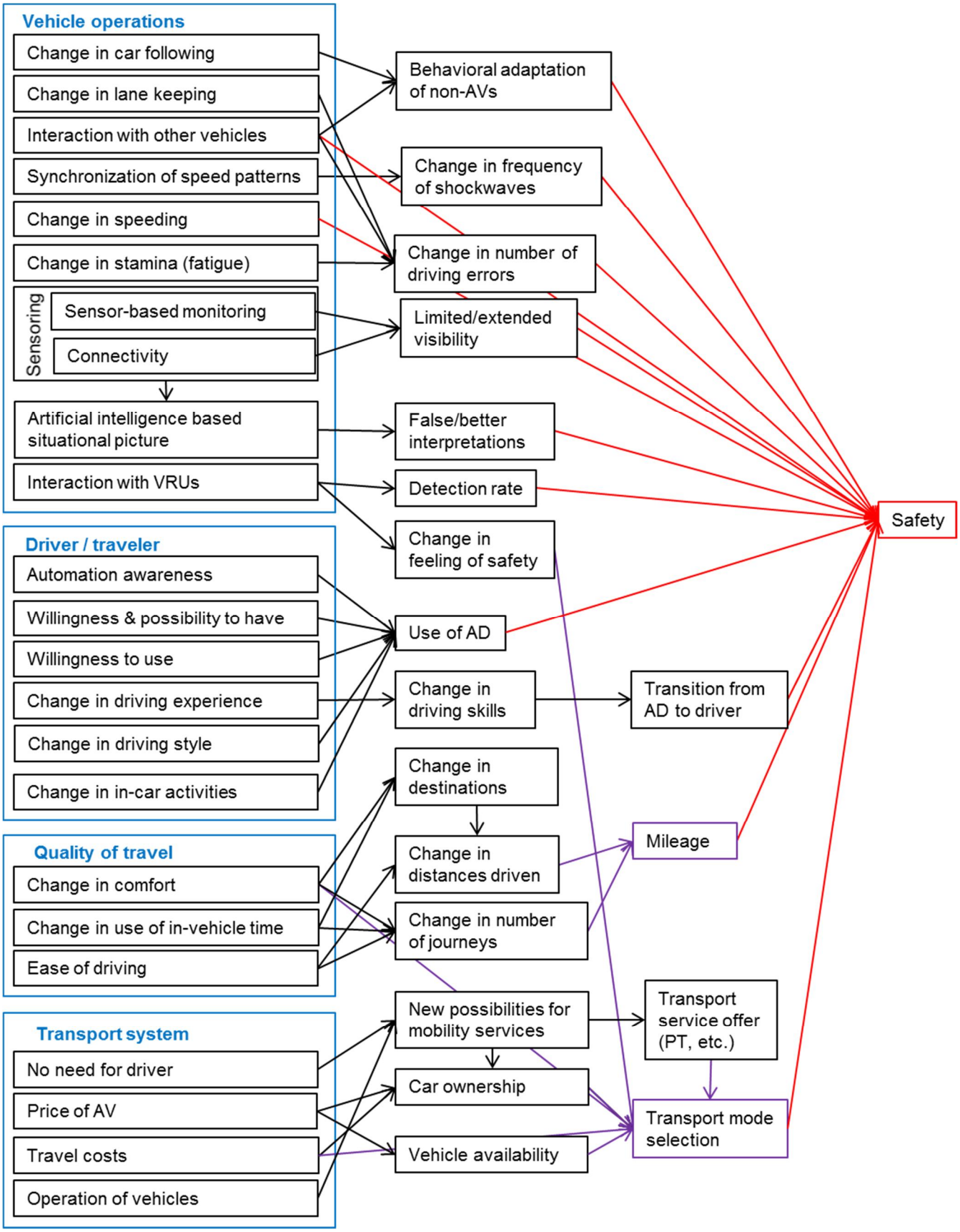

Figure 3. Impact paths of automated driving for safety

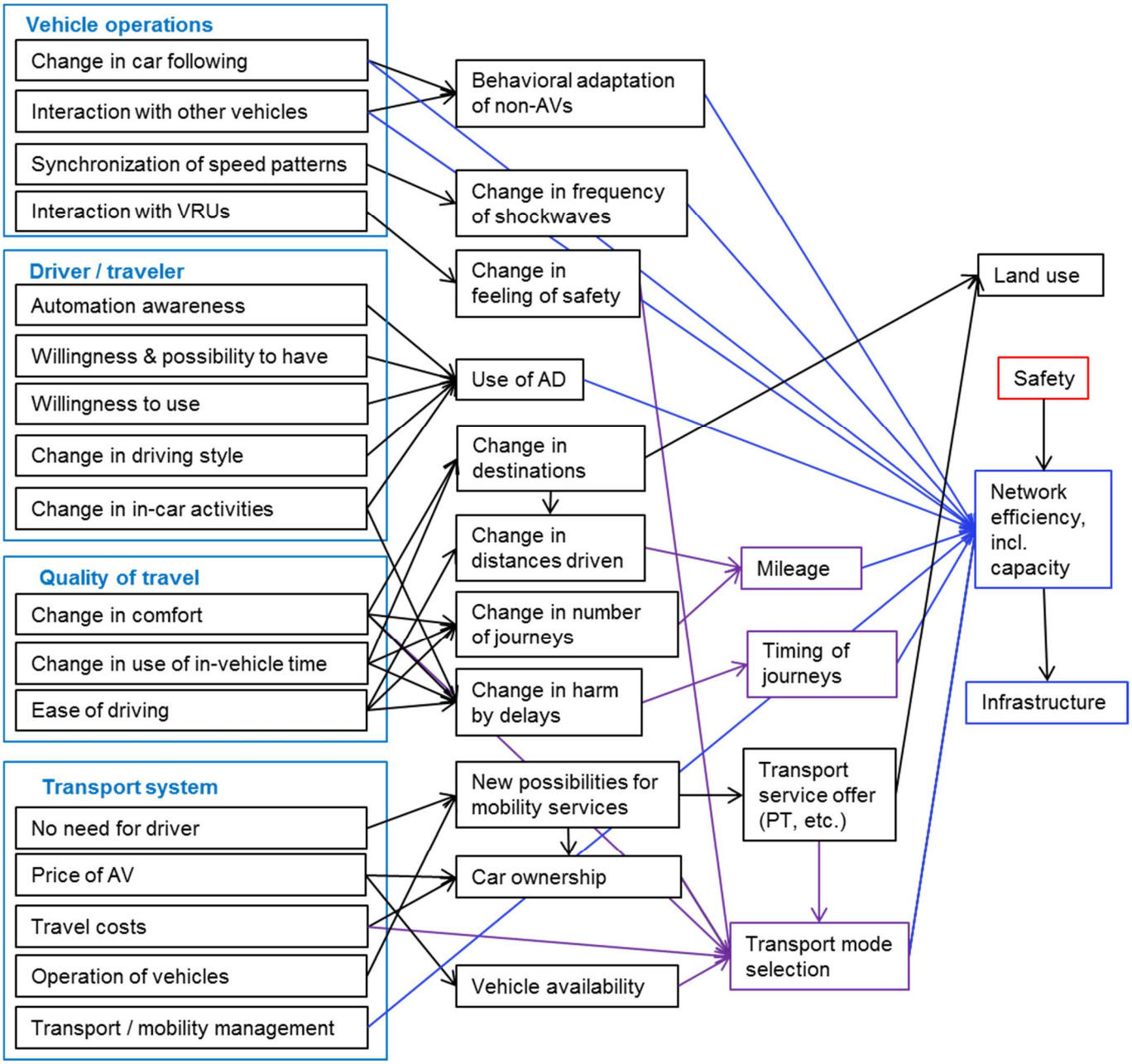

Figure 4. Impact paths of automated driving for network efficiency including capacity, and infrastructure as well as land use

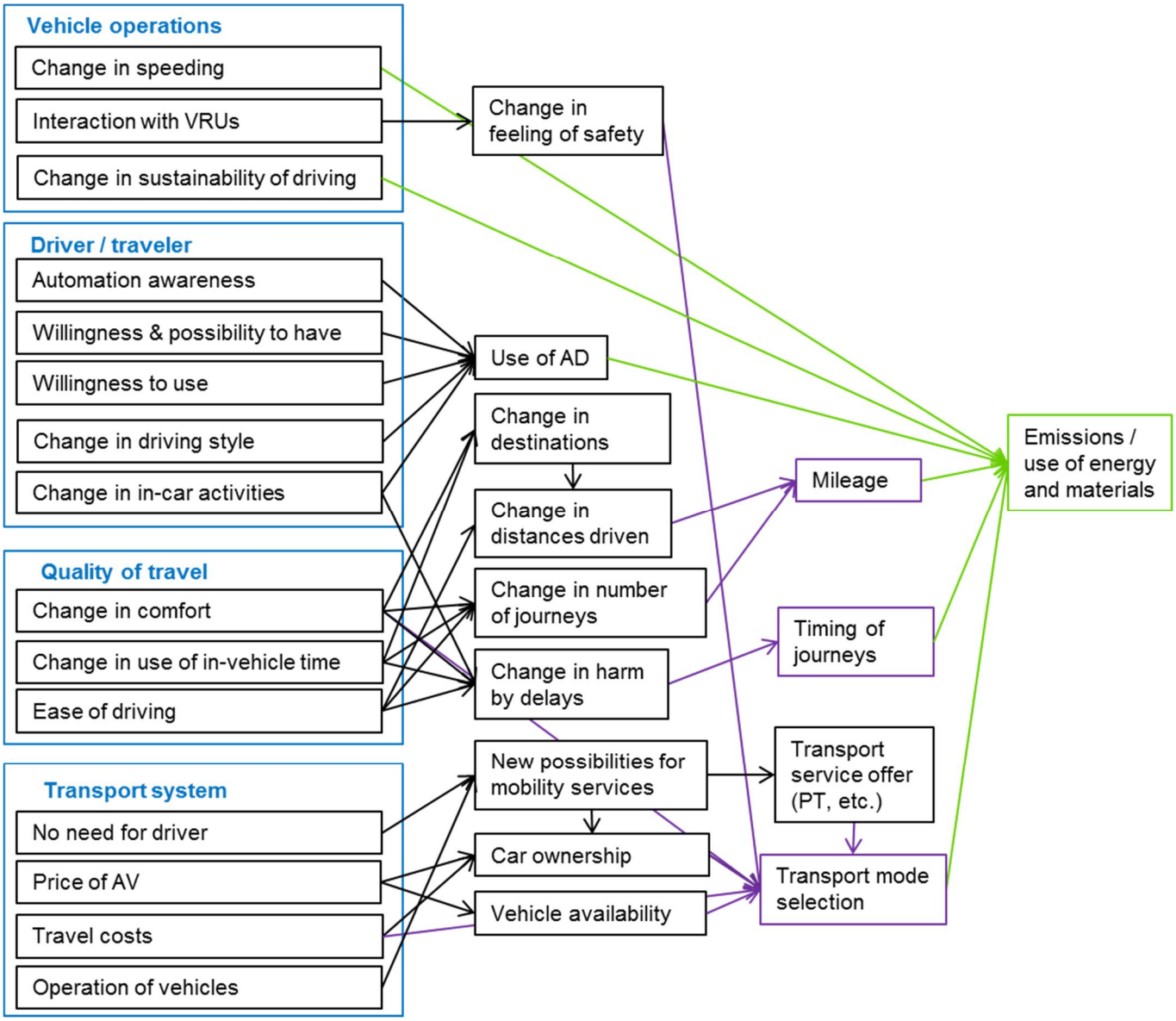

Figure 5. Impact paths of automated driving for emissions and use of energy and materials

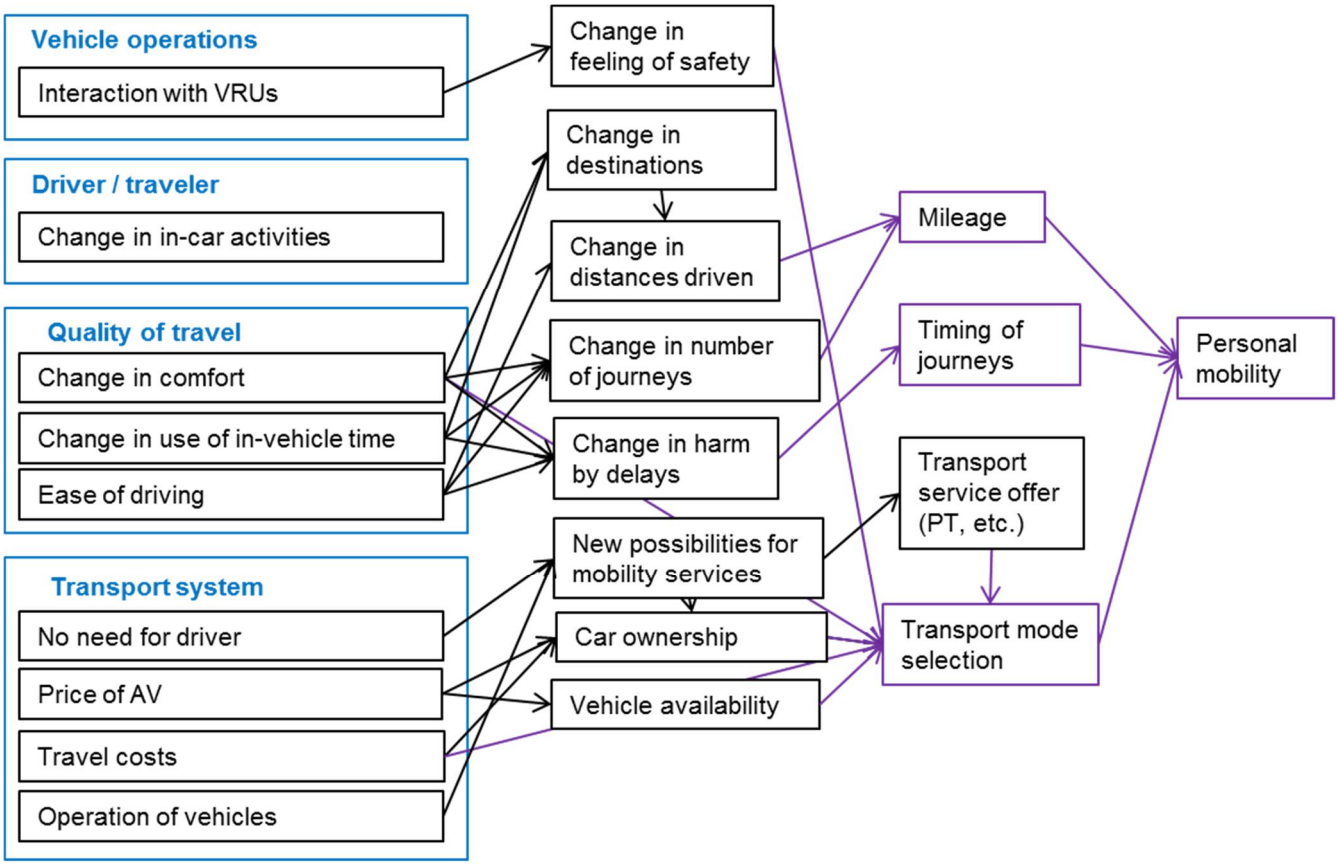

Figure 6. Impact paths of automated driving for personal mobility

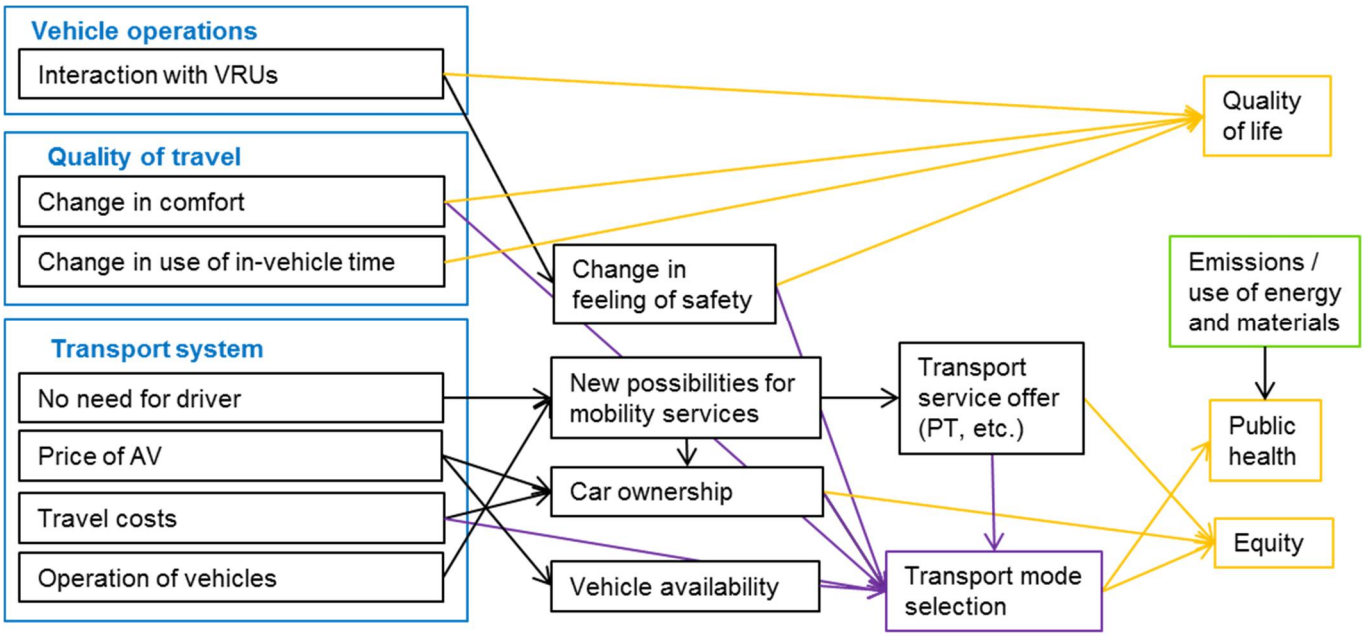

Figure 7. Impact paths of automated driving for quality of life, equity, and health

The impact paths presented above should be elaborated further for the system/service under evaluation adding also the direction of change. Figure 8 provides an example for that.

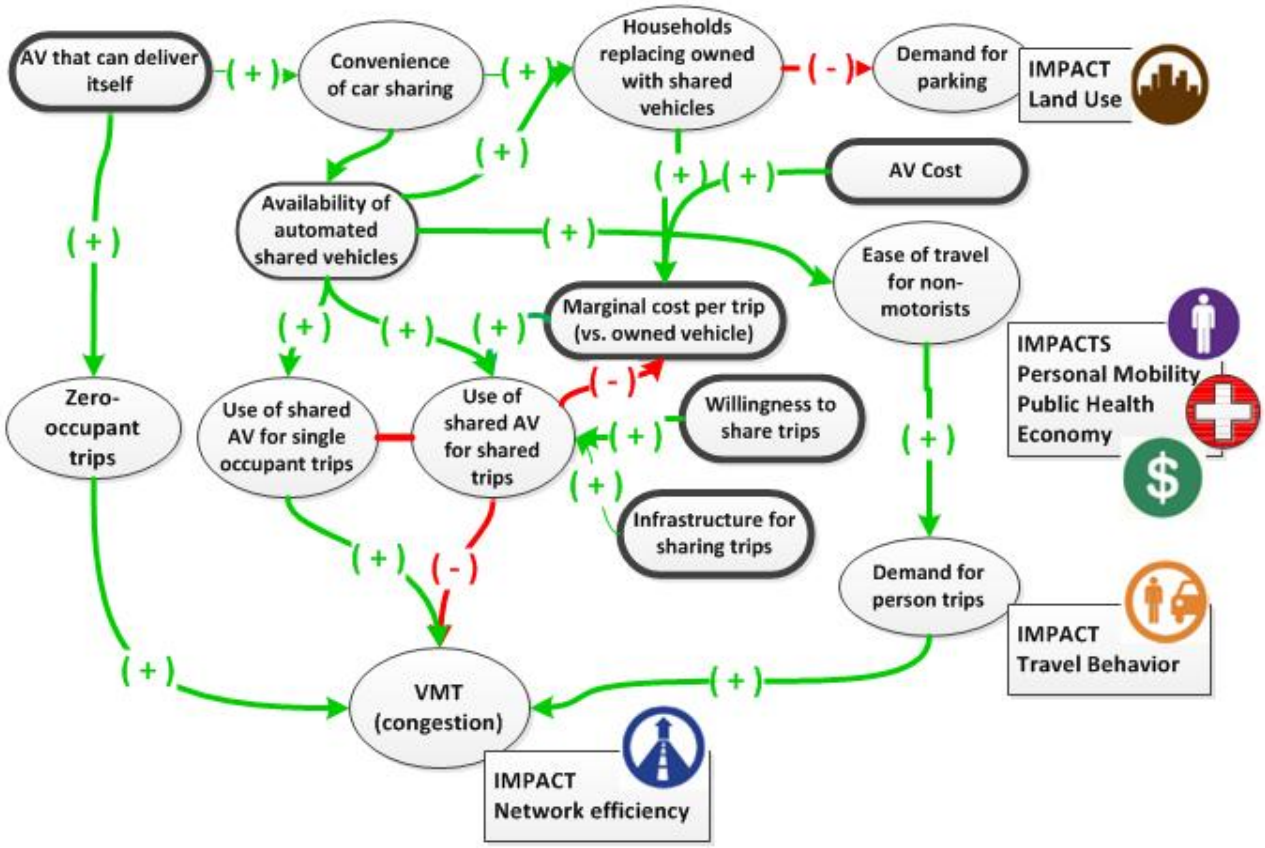

Figure 8. Example of a detailed impact path of 'AV being able to deliver itself'. Note that the green plus signs and red minus signs indicate whether there is an increase or decrease, not whether the change is good or bad.

4 Recommendations for experimental procedure

4.1 Study design

Field operational tests (FOTs) are typically used to gather evidence to assess the impacts of automated driving. The FESTA methodology (FOT-Net 2014) provides an extensive set of recommendations for developing an experimental procedure for Field Operational Tests. FESTA is designed for FOTs in general, and does not target AD studies in particular. Yet, many principles from FESTA are relevant here.

The first step when planning an FOT is to identify and specify the concepts (AD functions, systems, or new services) where considerable knowledge about their impacts and effects in realistic (driving) situations is of major interest. For automated driving this step may be a major one, as automation may come in different forms; it could be a suite of automated functions but also completely new types of driverless vehicles or services utilizing these vehicles. The description should include technical aspects (like operational area and the control logic); see the description of classification of system and service provided in chapter 2.1). It should also include aspects from the user point of view (such as potential user settings, handover, and human-machine interface (HMI)).

To reach this goal, several steps need to be taken, starting from a description of the automated functions down to an adequate level of detail in order to fully understand objectives and limitations and to derive reasonable use cases. Use cases are a means to describe the boundary conditions under which the automated function is (intended to be) tested; in other words, how we should expect the vehicle to behave under what circumstances. It might also be of interest to define the performance when certain preconditions for the functioning of the AD function (for example when the road markings are not visible) are not met and to identify unintended and unforeseen effects.

Starting from the definition of use cases, specific research questions need to be identified. Research questions are directly related to the impact areas that are to be investigated. First research questions are posed from impact area specific theories point of view (top-down) but also from the system/service under evaluation point of view (bottom-up) to make sure that all relevant questions are considered. Typically, this leads to a list which is too large to be covered by the evaluation. Thus, a prioritization is needed to select the most relevant research questions which the experimental design can provide the answer for.

The next step is to define statistically testable hypotheses for the prioritized research questions and find measurable indicators to test the hypotheses. Whereas research questions are general questions phrased as real questions ending with a question mark to be answered by compiling and testing related specific hypotheses; hypotheses are statements which can either be true or false. Hypotheses will be tested by statistical means. Defining testable hypotheses may be quite a challenge for road automation studies, as we cannot always predict what the effects are going to be. Hypotheses can only be tested by means of performance indicators. So after establishing these indicators, measures need to be defined and an experimental design to be developed. The following elements need to be determined:

- Characteristics and number of participants
- Characteristics of the experimental environment, such as location, road type, traffic conditions, weather, time of day and season.

It will not always be possible to test automated vehicles in a naturalistic environment. Sometimes a more artificial one needs to be used, such as a location with no other (or limited) motorised traffic or with dedicated lanes. Many AD studies will be performed utilising prototype vehicles, whose performance may not be the same as in the planned production vehicle. There may be failures that will be addressed in the next prototype or production phase. This needs to be addressed in the evaluation.

Most importantly, a lesson learned from all FOTs conducted so far, is that the whole chain, from logging and pilot execution to the analysis, should be piloted before starting the full-scale field tests, allowing for changes in the study design and making sure no technical problems remain.

4.2 Baseline

In FESTA Handbook (FOT-Net 2014), it is recommended that driving with the system is compared with driving without it (the baseline). For fully automated vehicles we no longer have a system that can be viewed as independent from the vehicle itself, the whole vehicle is now the system. Some forms of automation, like autonomous or driverless vehicles, mean a radical change in transport, with no baseline available. Comparison with the "old" situation may not be very useful, and studying new emerging patterns may be of more interest. Studying effects against a baseline is important if decisions have to be made on whether the introduction of new systems is desirable. If automation is seen as a process that will continue anyhow, a baseline becomes less important. Similar questions occurred with the introduction of nomadic devices. It is not so interesting to compare the behaviour of travellers without and with a smartphone as their penetration rate went up so quickly that comparison became meaningless, other than for historic reasons. Still, we may want to evaluate the effects of AD in comparison with the current situation. Below we will discuss several options for a baseline.

It might be ideal if we could compare automated driving with non-automated driving (SAE 0). However, there are several reasons why this is not so easy. In the first place, some current vehicles already have some automated functionalities and can be considered to belong to SAE levels 1 or 2. Thus, a traffic flow of 100% non-automated (SAE 0) vehicles is even now only theoretical or belongs to the past. As vehicles and traffic evolve also in other ways than just in relation to automation, comparison to something from the past does not give the true impact compared to the current or future situation.

If the baseline is chosen to be the prevailing vehicle population of the time when the automation FOT is conducted, we will always be comparing different kinds of baseline and a meta-analysis will be difficult to perform. If this option is selected, data and results from Naturalistic Driving Studies might serve as the "baseline." In these studies, "normal" everyday driving is studied (Eenink et al. 2014). This behaviour could be compared with the participants' behaviour when driving in automated vehicles.

If a theoretical traffic flow for a certain level of automation is selected as baseline (any automation level lower than the tested vehicle may be selected), attention must be paid to selecting the automated functionalities of the baseline vehicle or vehicle flow that are meaningful for the impact assessment purposes. A vehicle belonging to certain level of automation may be very different from another vehicle belonging to the same automation level if different aspects of driving have been automated. Thus, if parking behaviour of automated vehicles is studied, the automated parking functionalities are the key criterion in selecting the baseline.

If the comparison is made on a one-to-one level, the baseline vehicle may be a conventional vehicle or a vehicle with lower level automation. However, when impacts are assessed at the level of the entire traffic flow, the penetration of different levels of automation is a key issue, as the penetration of connected or autonomous vehicles as well as the connectivity itself may impact on, for example, the car-following behaviour of vehicles. One could compare situations where there are many automated vehicles in a certain area, versus few or just one. This may require a more experimental set-up, bringing vehicles together, like a study on platooning would do compared to studying single vehicles.

When selecting research questions and hypotheses and building a test design, we must bear in mind that things should not be compared when they are not comparable. For example, the percentage or duration of eyes-off-the-road may be much higher with automation than in conventional vehicles, but is this of any interest? Thus, the baseline should always be selected wisely and guidance from a methodology would be useful.

4.3 Controlled testing

Although as naturalistic approach in the field tests as possible is typically requested by the impact assessment, sometimes it may not be feasible for the automated driving studies.

In case the vehicle with which the tests are made is still a prototype and a so-called safety driver is mandatory to sit beside the test subject of the evaluation, a controlled test approach is practically the only option. The same applies if a large group of test subjects is targeted and the test vehicle fleet is small. If connectivity is evaluated with a small test vehicle fleet, controlled tests are needed to provide a sufficient number of encounters (e.g., with two connected vehicles interacting).

The benefits of controlled tests include effectiveness in data acquisition (i.e. high number of events recorded in relation to the length of data collection period) and smaller variance due to differences in the driving conditions and environments.

The drawback is clearly the short nature of tests per participant. The controlled tests seldom include frequent repetition of AV use for long periods. Therefore, the long-term impacts cannot be seen. This affects e.g. mobility impact assessment as new mobility patterns take time to form. In case a safety driver is on board, his/her presence will also influence the behaviour of the test subject (e.g. you do not start to sleep or mal-use the AD functionalities while being directly observed). Another drawback is the smaller variance in external conditions (weather, road types, traffic situations, etc.).

4.4 Use of simulation models

With the new impact areas that were not looked at in the Advanced Driver Assistance System (ADAS) evaluations and other previous FOTs, new methods need to be developed. With their indirect nature and long time to form, they are typically not anything that traditional FOTs can cover.

The use of traffic simulation models can provide the capability to assess the direct impacts of the new/planned ADAS (lower level of automation) onto traffic flows. Since the traffic simulation is often criticized as the black-box, it is required to be modelled with sufficient transparency and rationality supported by the engineering validation process.

In the International Joint Report (IJR) on the "Guidelines for assessing the effects of ITS on CO_2 emissions" (Energy-ITS Project, ECOSTAND and PATH, 2013; Figure 9), it is recommended that the simulation models should be clarified with the reference model which figures out the causal relationships of the ADAS functions and the traffic phenomena leading to energy saving and CO_2 reduction. The IJR also recommends that the verification process should follow the model clarification to ensure the quantitative relationship of each causal relationship appeared in the reference model, and the validation process to check the model outcomes are similar to fresh real data which might be collected through the small but precise field observations or the coordinated tests.

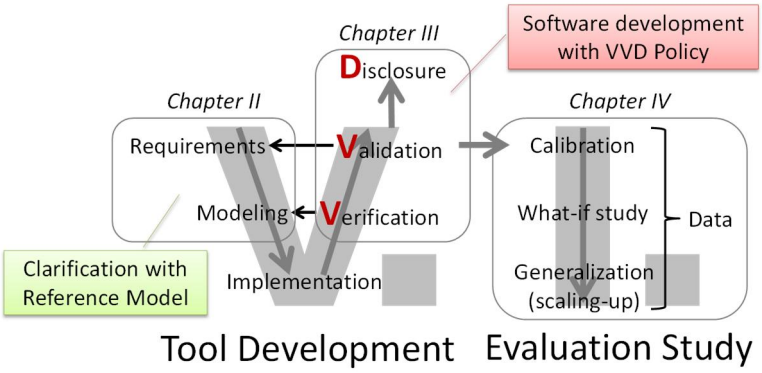

Figure 9. The structure of IJR

There would be the expectation to utilize the simulation models access the social impacts on economics, quality of life, etc. The keys of those assessments are to predict how the ADAS penetrate in the future market and how the travel behaviours of the people will change. The conventional macroscopic modelling using statistics will provide the solution if there is similar and well-studied market under the big assumption that the people will behave as before. Unless we can accept such an assumption, further investigation will be required.

The biggest expectation on the simulation would be to assess the impacts on safety. For this purpose, the microscopic human-vehicle modelling is actively investigated. In general, the modelling tries to identify the mechanism how the human recognition and reaction will lead to the vehicle manoeuvrings and dynamics, and to explain that the ADAS covering the human errors will prevent collisions and accidents. Such direct modelling approaches will provide comprehensive but qualitative answer to the question whether the ADAS will work correctly or not. However, continuous effort is still needed to identify the quantitative relationships in the human model. The use of the driving simulators is encouraged.

Another approach for the safety assessment is to use the microscopic traffic simulation models to estimate the surrogate measures (FHWA, 2001) such as 'Time-to-collision', 'Post-encroachment-time', etc. By using well-calibrated traffic simulation models in respect of those surrogate measures collected through reliable observations, we may predict how the new/planned ADAS will change the driving behaviours to the safer direction. However, as there is a gap between the changes on those surrogate measures and accident reduction, the further investigations with the statistical analysis are still expected. Continuous video survey with effective image processing technology will be the key to collecting massive and precise vehicle motion data.

5 Recommendation for data sharing

5.1 Reasons for data sharing

It is unlikely that any one study will be able to answer all questions on the impact of road automation nor collect data for that. This means that we will need data from different studies to analyse the wider impact. By sharing data between organisations and projects, new knowledge might be gained about what will happen when automated vehicles drive in real traffic.

From experience in previous FOTs, we know that often large datasets have been collected but because of limited resources, both in terms of time and money, not all data are analysed and impact assessment is often limited. In the US, the Research Data Exchange (https://www.its-rde.net/) has been set up to allow for datasets to be re-used by third parties for new analyses. In Europe, a coordination and support action FOT-Net Data built a Data Sharing Framework (Gellerman et al. 2015) to support data sharing and re-use.

Data sharing and re-using data is a good idea for making efficient use of the large efforts needed to collect the data. It is also allowing researchers who do not have the means to collect new data to answer research questions or providing others with better quality or larger datasets than they could collect. Data from previous FOT and Naturalistic Driving Studies may also be re-used, as this may provide information about the current situation, to be used as a baseline. Also knowledge about how human drivers tackle problems in traffic may provide ideas for informing and improving automated functions.

Data sharing between different countries may provide new knowledge about different conditions under which the automated vehicles drive and is of value for an internationally oriented automotive and service industry.

Sharing and re-using data can be a major step forward in our understanding of the behaviour of transport users and systems. In Europe, the European Commission is stressing this need for data to be open and shared, as they are one of the main sponsors of data collection. A wealth of information is hidden in the datasets that have been collected in recent years and that will be collected on automated driving in the coming years, so the question is how we will be able to generate new knowledge out of these datasets.

Re-using research datasets is seen to have several benefits on a societal level: it will yield further research results at minor additional cost, support education, improve collaboration and thereby create trust in providing more data, and contribute to market introduction of new systems by enabling several organisations to assess benefits. For such reasons, across different fields of science, publicly funded research projects will be required to share more of their collected data in the future.

5.2 Obstacles for data sharing and their solutions

Data sharing and re-use is easier said than done. There are five main obstacles:

- Data are valuable and may contain competitive information. Therefore, it cannot always be shared in the format it is collected or at all. Data may contain proprietary information regarding the performance of the technology used. This area need more attention in automation compared to previous studies due to the responsibility issues within automation.
- Datasets may also contain privacy-sensitive data, such as personal data about the driver, or other data that can be traced back to persons, not only those other road-users participating in the study

but random traffic participants happening to be around the vehicles. Specifically, video data are very sensitive. Participants may not have given permission to share data with other organisations and for other purposes.

- Looking at international data sharing, the different legal and ethical conditions in the involved countries might impose constraints and difficulties in sharing data.
- Data are not always easy accessible. Only if the dataset is well-documented and contains a rich set of metadata is it possible to create a larger re-use of data collected by others. Not only the data, but also the tools with which the data were processed may be needed.
- Storing, maintaining and opening data after a project has a cost; it may be difficult to find a good financial model for covering or sharing these costs. The owner(s) of the data have also made large efforts (and usually put also their own funding) to collect data and build up the data infrastructure and tools. Data providers and data re-users may have different views on this. It is therefore important to find win-win situations between the data provider and data user in further re-use of the data, to compensate for the efforts made to provide easily accessible data.

5.3 Data sharing framework

In the FOT-Net Data coordination and support action, a data sharing framework (Gellerman et al. 2015) has been developed to address these issues. The framework is illustrated in Figure 10.

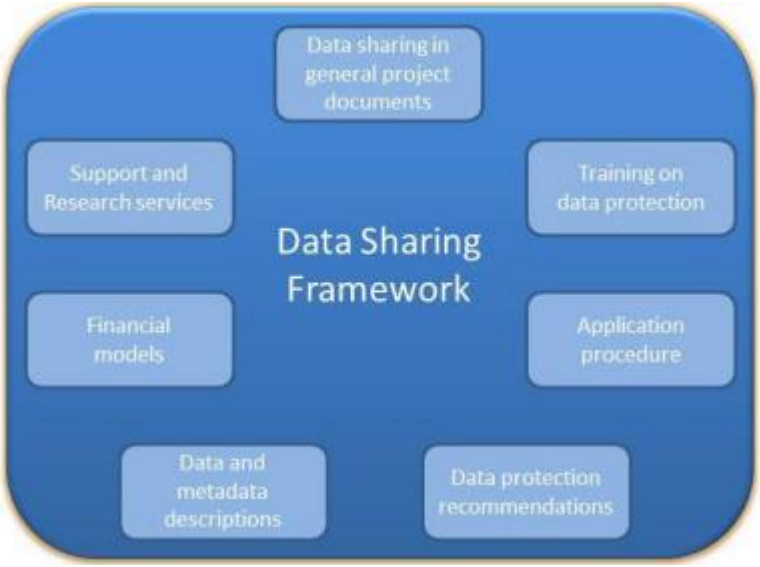

Figure 10. An overview of FOT-Net's Data Sharing Framework (Gellerman et al. 2015)

The Data Sharing Framework consists of seven areas, all essential for a smooth data sharing process:

- Project agreements, such as the grant agreement together with the description of the work, the consortium agreement, the participant agreement and external data provider agreements set the pre-requisites and the borders for data sharing together with legal and ethical constraints. The framework provides specific topics to address.

- The availability of documented, valid data and metadata, including a recommendation for a "standard" description of the data, e.g. standard format and the related attributes such as sampling frequency and accuracy, and the description of the study design.

- Data protection requirements both on the data provider and re-users´ analysis site, including security procedures.
- Security and personal integrity training content for all personnel involved.
- Support and research functions, to facilitate the start-up of projects and also e.g. offer processed data for researchers not so familiar with FOT/NDS data. The support also includes the availability of analysis tools.
- Financial models to provide funding for the data to be maintained and available, and access services.
- Last, but not least application procedures including content of application form and data sharing agreement.

5.4 Common dataset

The sharing of data from road automation studies and the related analysis would benefit substantially, if a common, minimum dataset could be defined, that studies all over the world collect and share. This does not have to be a large set or include sensitive data. The data probably need to be pre-processed and anonymised to ensure that no confidential or personal information is shared, to facilitate a larger re-use. Examples of data that could be useful to allow cross-study comparison are variables describing vehicle behaviour such as speed, distance to other traffic participants, events and incidents, as well as user questionnaires shedding light on road user acceptance.

It is important to build a common view among the stakeholders of the benefits of such a minimum dataset of automation data. The key is to create a win-win situation, with a picture of the future use of the data resolving questions regarding the impact of automation and removing road blocks for the implementation of automation. The advantages for each of the stakeholders providing and using the data must be clear. The focus should be on sharing data from road automation studies. The advantages probably need to stretch into the deployment phase though, to develop the full picture of potential benefits and create the necessary incentives for sharing data.

The common dataset need to be agreed within the coming 1-2 years, to be able to be collected and provided by the projects, currently planned and decided.

6 Conclusions

This framework is designed to be a high-level evaluation framework for assessing the impact of automation in road transportation and to harmonize these evaluations. The motivation for building this framework is that the potential impacts of automation are far reaching and complex. There are high expectations on the contributions of connected and automated vehicles to societal goals. International harmonization helps to maximize the insight obtained from single studies, supports meta-analysis and making better use of each other's findings. The framework was developed by members of the Trilateral Impact Assessment Sub-Group for Automation in Road Transportation.

The framework is meant for governments to support policy analysis and long-range scenario-based planning, for automakers and after-market equipment manufacturers to better understand the potential benefits of their offerings, for designers of field tests to ensure that the information gathered maximizes the value of the test, and for those making the impact assessment as a starting point in design of their evaluation work.

The framework provides recommendation for classifying automation implementations and determining impact areas to be assessed. It presents the impact mechanisms through which automated driving is expected to impact our life, covering both direct and indirect impacts. In addition, it provides recommendations for experimental procedure and data sharing.

This version of the framework is the first full draft to be presented to the target group. Feedback will be collected and later updates will be made to ensure the acceptance and use of the framework in the evaluation studies of road transport automation. Future tasks also include the definition of the minimum common dataset to be collected and shared.

As part of its work in 2017, the Impact Assessment Sub-Group will continue to identify and refine KPIs based on current and planned FOTs and studies and identify those which are the highest priority for international harmonization. It will also continue work on defining the common dataset to be able to be collected and provided by the projects, currently planned and decided.

Acknowledgement

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